First Transport Code Simulations Using The TGLF Model

by
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in collaboration with
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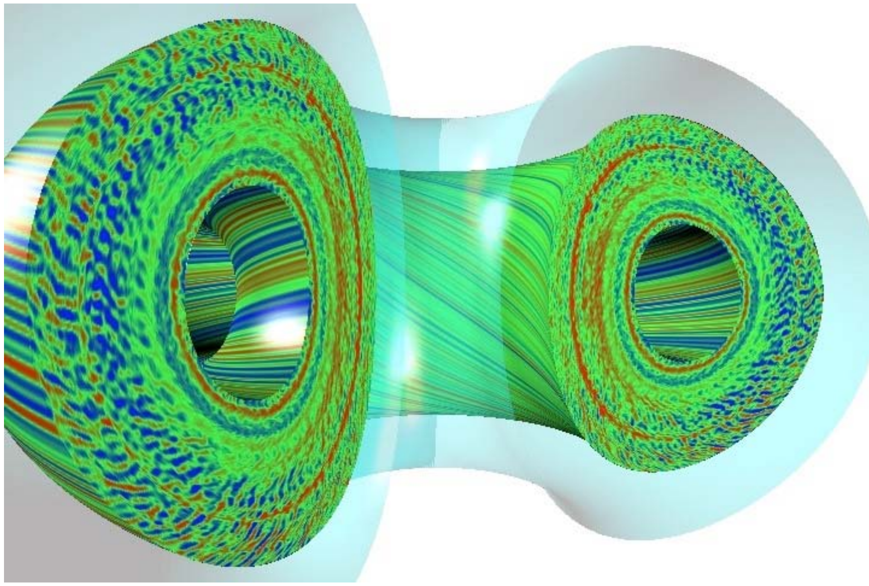

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Overview

- **Philosophy in developing the Trapped Gyro-Landau-Fluid (TGLF) transport model has been to obtain best fit to gyrokinetic simulations, then use experimental data to test the theory**
- **Fitting of TGLF saturation rule to a nonlinear database of 83 GYRO ITG/TEM gyrokinetic simulations with shaped geometry**
  - QL theory works amazingly well ! TGLF energy fluxes within 20% of GYRO results
  - TGLF shows better agreement with GYRO simulations compared to GLF23 model and reproduces GYRO result of elongation effects on transport, ExB shear
- **Testing of TGLF transport model against experimental profile database (over 500 transport runs in this paper)**
  - TGLF shows better agreement than GLF23 with a database of 96 discharges from DIII-D, JET, and TFTR
- **Sensitivity Studies**
  - Boundary conditions, geometry, ExB shear
  - High-k transport
  - Finite beta effects, density evolution
- **Summary and future work**

The TGLF Gyro-Landau-Fluid Transport Model

- TGLF is the next generation GLF model with improved comprehensive physics compared to its predecessor, GLF23
  - Model valid continuously from low-k ITG/TEM to high-k ETG
  - Extended range of validity (e.g. pedestal parameters, low aspect ratio)
  - Valid for shaped geometry using Miller local equilibrium which replaces s-α high aspect ratio shifted circular geometry
  - Includes finite beta physics, improved electron physics
- TGLF solves for the eigenvalues using a set of 15-moment gyro-fluid equations per species for linear drift-wave instabilities using 4 Hermite basis functions (2 species x 15 eqns x 4 basis functions => 120x120 matrix)
  - GLF23 4-moment 8x8 matrix, 1 poloidal trial basis function
- TGLF has been systematically tested against a database of about 1800 linear growth rates and frequencies created using the GKS gyrokinetic code (Staebler, Kinsey, Waltz, PoP 12, 102508 (2005))

  Avg σ (γ) = 11% for TGLF, 38% for 1997 GLF23
- A model for the nonlinear saturation levels of the turbulence using the linear mode growth rates has now been found for shaped geometry

Fitting of TGLF saturation rule to nonlinear GYRO simulations

TGLF Saturation Rule was Fit to GYRO Nonlinear ITG/TEM Simulations Using Miller Geometry

- **Transport fluxes are computed using a saturation rule with the magnitude of the total eigenvector (see Staebler UP8.00050)**

$$\Gamma = \sum_{k_y} n c_s \left[\frac{\mathrm{Re}\left\langle i\hat{k}_y \tilde{\Phi}^* \tilde{n} \right\rangle}{\tilde{V}^* \tilde{V}} \right] \overline{V}^2 \qquad Q = \frac{3}{2} \sum_{k_y} p c_s \left[\frac{\mathrm{Re}\left\langle i\hat{k}_y \tilde{\Phi}^* \tilde{p}_T \right\rangle}{\tilde{V}^* \tilde{V}} \right] \overline{V}^2$$

[ ] = quasilinear weight

$$\overline{V}^2 = C_{norm} \left(\frac{\rho_s \hat{\omega}_{d0}}{a} \right)^2 \left(1 + \frac{T_e}{T_i} \right)^2 \left(\frac{1}{\hat{k}_y^{c_k}} \right) \left[\frac{\hat{\gamma}_{net}^{c_1} + c_2 \hat{\gamma}_{net}}{\hat{k}_y^4} \right]$$

Model for saturated intensity

$C_{norm} = 32.5 \quad c_1 = 1.55 \quad c_2 = 0.534 \quad \alpha_E = 0.3\sqrt{\kappa} \quad 0.1 \le \hat{k}_y \le 24$ (21 modes)

$$\tilde{V} = (\tilde{n}, \tilde{u}_{||}, \tilde{p}_{||}, \tilde{p}_T, \tilde{q}_{||}, \tilde{q}_T) \qquad \hat{\gamma}_{net} = Max\left[\left(\hat{\gamma} - \alpha_E \hat{\gamma}_E \right) / \hat{\omega}_{d0}, 0 \right] \qquad \hat{\omega}_{d0} = \hat{k}_y \frac{a}{R}$$

- **Coefficients & exponents in the saturation rule are found by minimizing the error between TGLF & GYRO energy fluxes for 83 nonlinear GYRO ITG/TEM simulations**

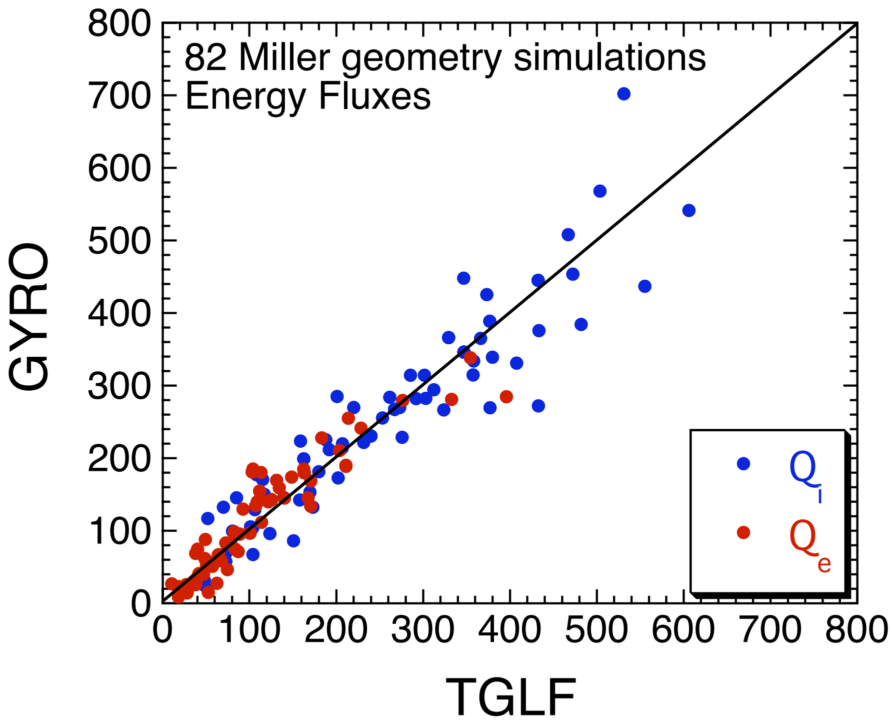
$$c_k = 0.0 \quad for \quad \hat{k}_y < 1$$

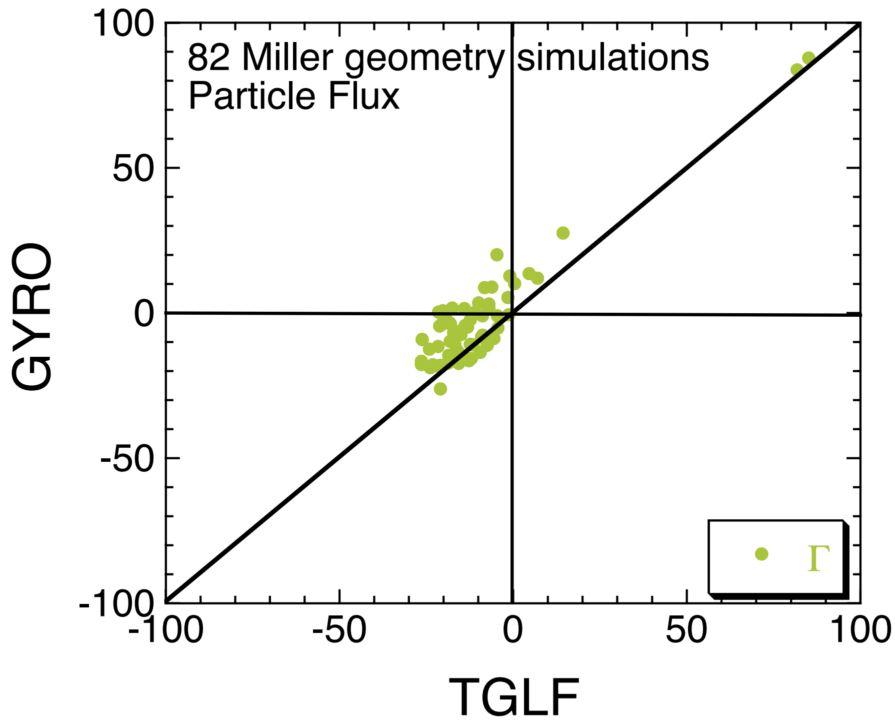
- **The high-k ($\hat{k}_y > 1$) part of the electron energy flux is adjusted to fit one GYRO coupled ITG/TEM-ETG simulation of the GA STD case with Miller geometry by modifying the $\hat{k}_y$ exponent**

$$c_k = 1.25 \quad for \quad \hat{k}_y \ge 1$$

TGLF Saturation Rule Fits the Energy Transport From 83 Nonlinear GYRO Miller Geometry Simulations Very Well

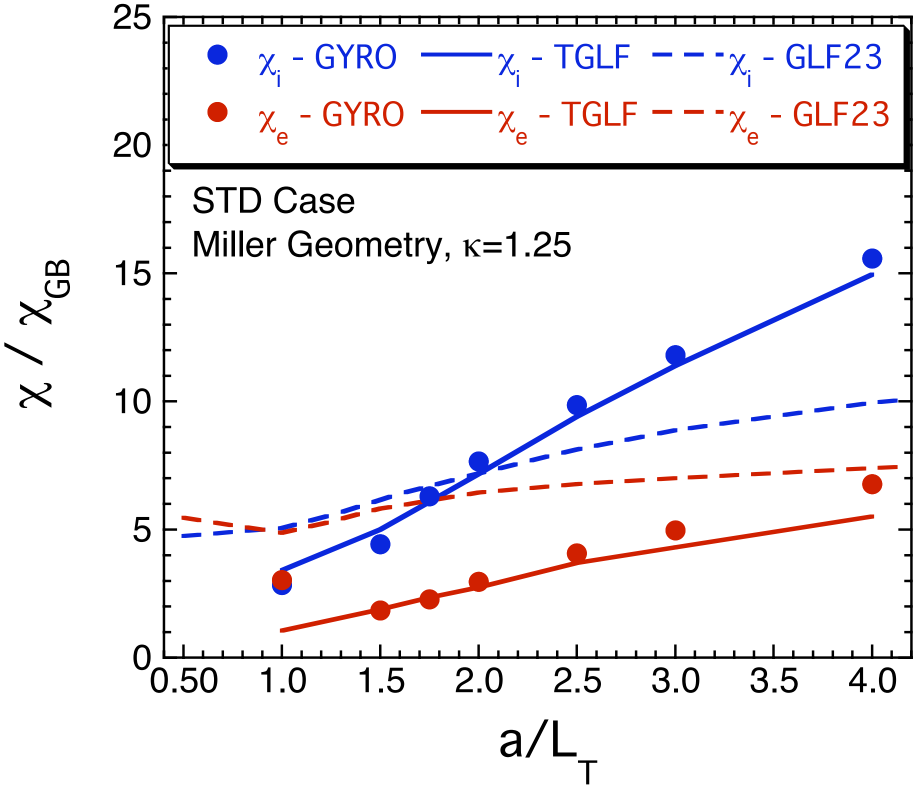
- **GYRO scans w/ kinetic electrons, Miller geometry, electrostatic, collisionless**
  - Also a version of TGLF fit to 84 shifted circle GYRO simulations
- **Use the 2 most unstable modes at each k_y**
- **Best fit has RMS errors of [17%, 20%] for [ion, electron] energy fluxes**

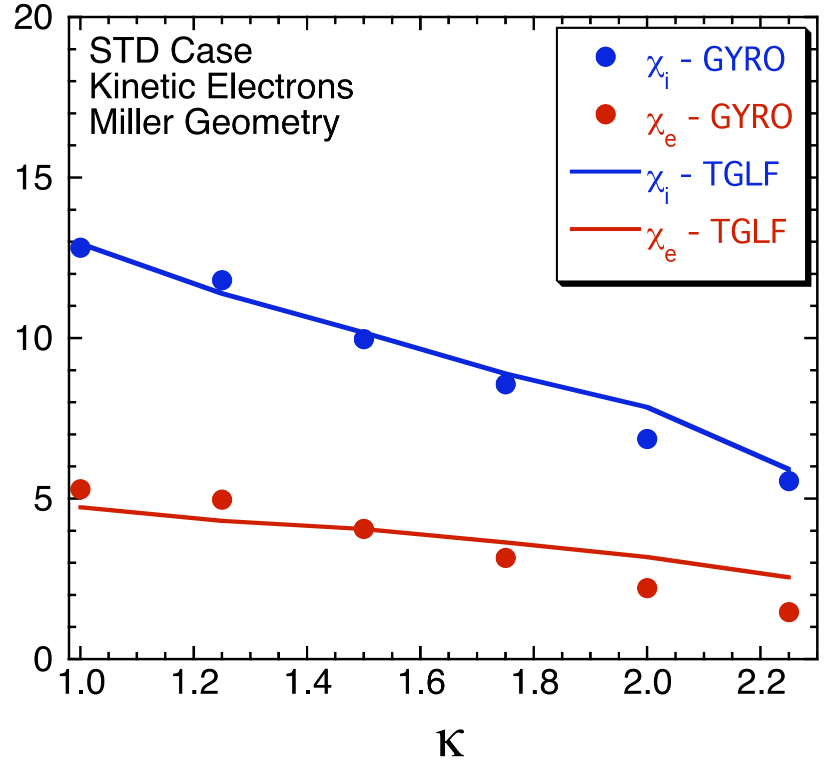




TGLF Demonstrates Better Agreement With GYRO Nonlinear Simulations Than GLF23

- **TGLF matches GYRO a/LT scan around GA-STD case with Miller geometry**
  - STD case: R/a=3, r/a=0.5, q=2, s=1, a/L_T=3, a/L_n=1, κ=1.0, δ=0, β=0, ν_{ei}=0
- **GLF23 low-k electron energy transport is systematically too large (red dashed line) and misses critical temperature gradient**
- **TGLF reproduces stabilizing effect of elongation seen in GYRO simulations**





Linear ExB Shear Quench Rule Has Been Implemented in TGLF and Shows Good Agreement With GYRO Simulations

- **TGLF compared to GYRO ExB shear scans for STD case with Miller geometry, different values of κ, δ=0, low-k only, kinetic electrons***
- **ExB shear rate with multiplier α_E is subtracted from maximum growth rate at each $k_\theta\rho_s$**

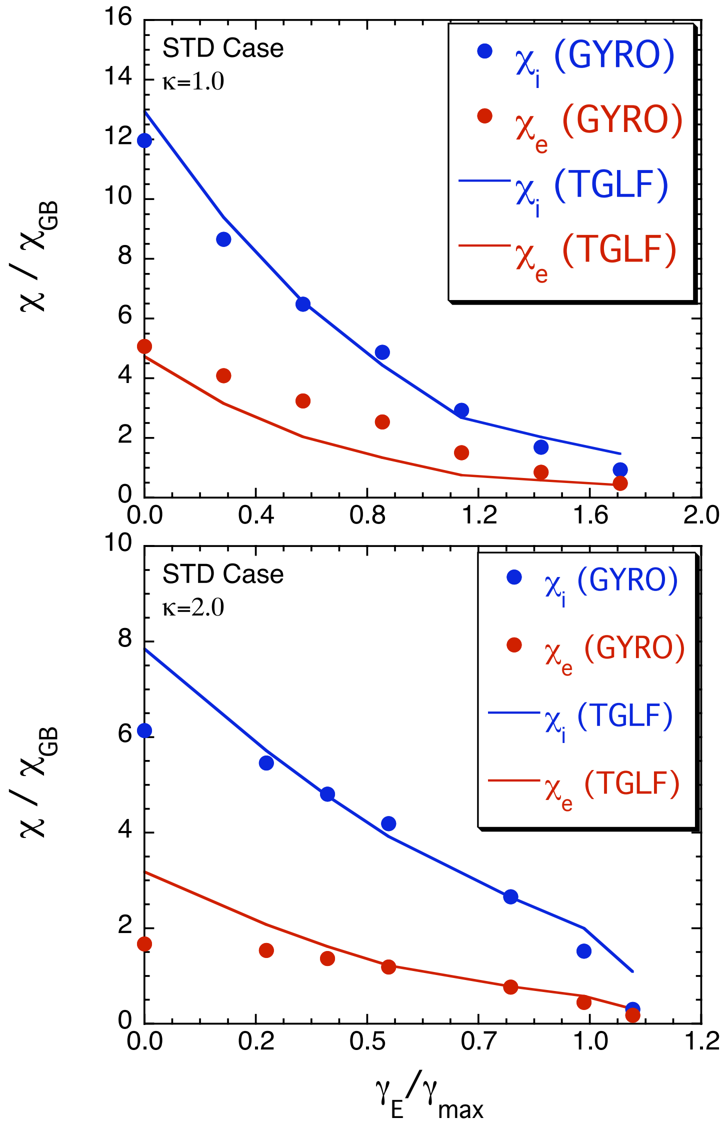
$$\hat{\gamma}_{net} = Max\left[\left(\hat{\gamma} - \alpha_E \hat{\gamma}_E\right)/\hat{\omega}_{d0}, 0\right]$$

Here,

$$\alpha_E = 0.3\sqrt{\kappa}$$

gives a good fit to GYRO ExB shear simulations with Miller geometry

See Kinsey, et al, Phys. Plasmas 14, 102306 (2007)



Testing of TGLF transport model against experimental profile database

A Profile Database of 96 Discharges From DIII-D, JET, and TFTR Has Been Assembled for Model Testing

- **The database is comprised of conventional L- and H-mode discharges**
  - 25 DIII-D L-, 33 DIII-D H-, 22 JET H-, 16 TFTR L-mode discharges
  - Most of JET and all of TFTR discharges in ITPA Profile Database
  - Most discharges are from parameter scans including $\rho^*, \nu^*, \beta, q, T_i/T_e, v_\phi$
  - Only considered discharges with toroidal rotation (v_ϕ) data present
  - 96 shot database supplemented with DIII-D hybrid database (27 shots)
- **Simulation methodology**
  - TGLF and GLF23 run in the XPTOR transport code and treated equally with same solver and data
  - Predict core Te and Ti profiles for a single time-slice taking densities, toroidal rotation profiles, equilibrium, sources, sinks from experimental analyses
  - Boundary conditions enforced at ρ=0.84 for L-, H-modes
  - First TGLF runs are electrostatic with hydrogenic ions only
  - Chang-Hinton neoclassical, neoclassical poloidal rotation for ExB shear
  - TGLF simulations performed on local Linux cluster usually with 40 processors CPU time ≈ 10 mins for 40 grid pts, 40 processors

Figures of Merit

- **Quantitative agreement measured by global and local figures of merit**

Avg. and RMS in incremental stored energy W_{inc} for i^{th} discharge

$$\langle R_W \rangle = 1/N \sum_i W_{s,i} / W_{x,i} \qquad \Delta R_W = \sqrt{1/N \sum_i \left(W_{s,i} / W_{x,i} - 1 \right)^2}$$

RMS and offset for temperature T profile at each j^{th} radial pt for i^{th} discharge

$$\sigma_{T,i} = \sqrt{\sum_j \varepsilon_j^2} \Big/ \sqrt{\sum_j T_{x,i}^2} \qquad f_{T,i} = \frac{1}{N} \sum_j \varepsilon_j \Big/ \sqrt{\frac{1}{N} \sum_j T_{x,j}^2}$$

$$\varepsilon_j = T_{x,j} - T_{s,j}$$

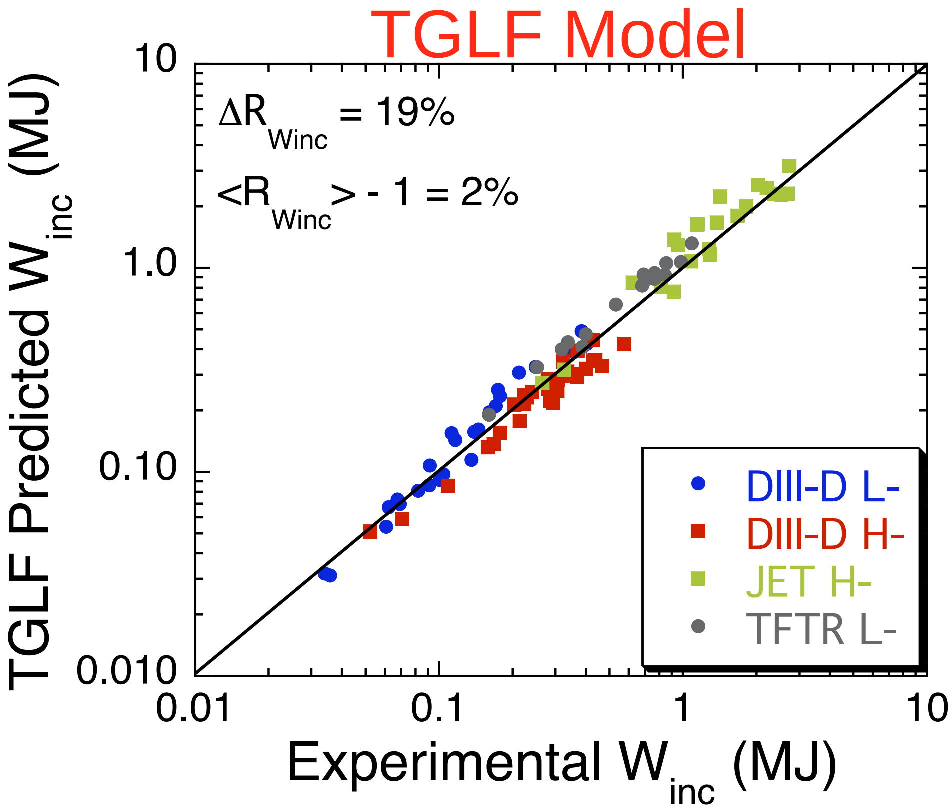
Deviation between Exp. Temp (T_x) and Simulation (T_s)

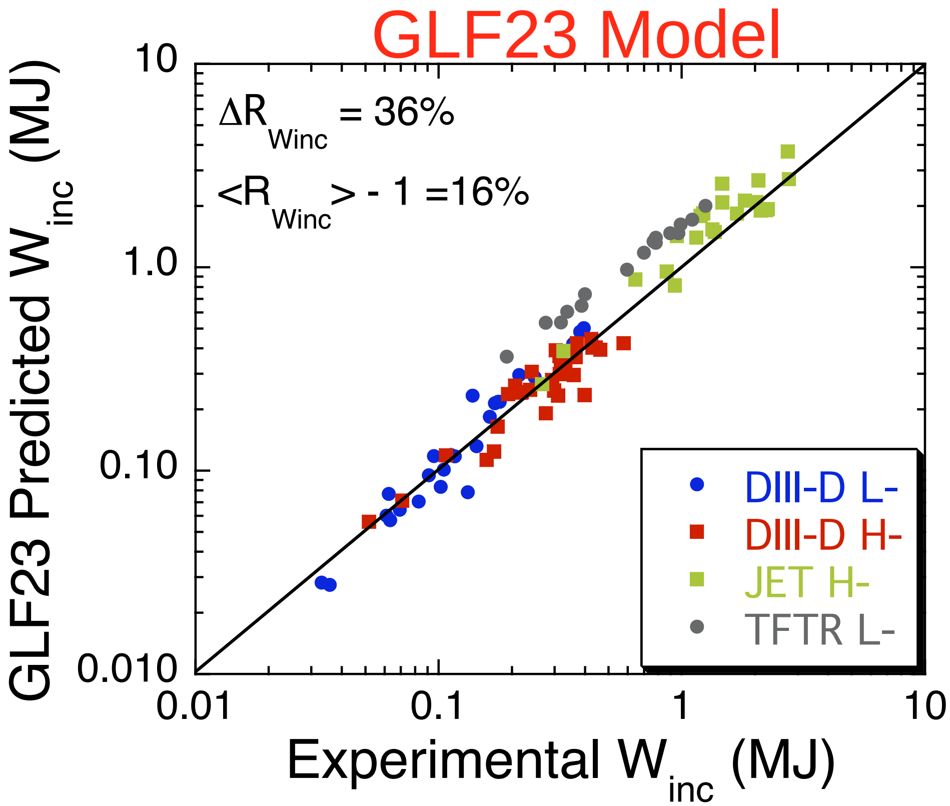
Avg RMS and offset for each dataset

$$\bar{\sigma}_T = \sqrt{\frac{1}{N} \sum_i \sigma_{T,i}^2} \qquad \bar{f}_T = \frac{1}{N} \sum_i f_{T,i}$$

TGLF Exhibits Lower Average Global Errors Than GLF23 for a Large L- and H-Mode Profile Database of 96 Discharges

- **Database: 25 DIII-D L-,33 DIII-D H-, 22 JET H-, 16 TFTR L-mode discharges**
- **Avg RMS errors in W_{inc} is 19% for TGLF, 36% for GLF23**
- **Offset in W_{inc} much smaller for TGLF (2% vs 16%)**
- **Avg RMS error in W_{tot} is ΔR_{Wtot}=10% for TGLF, 20% for GLF23**

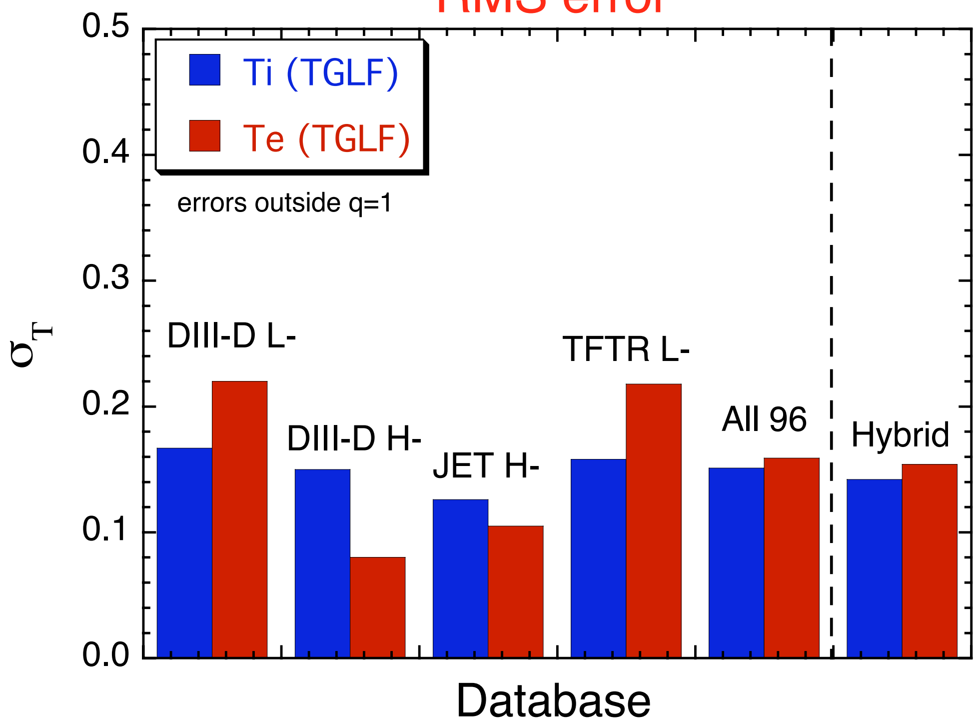




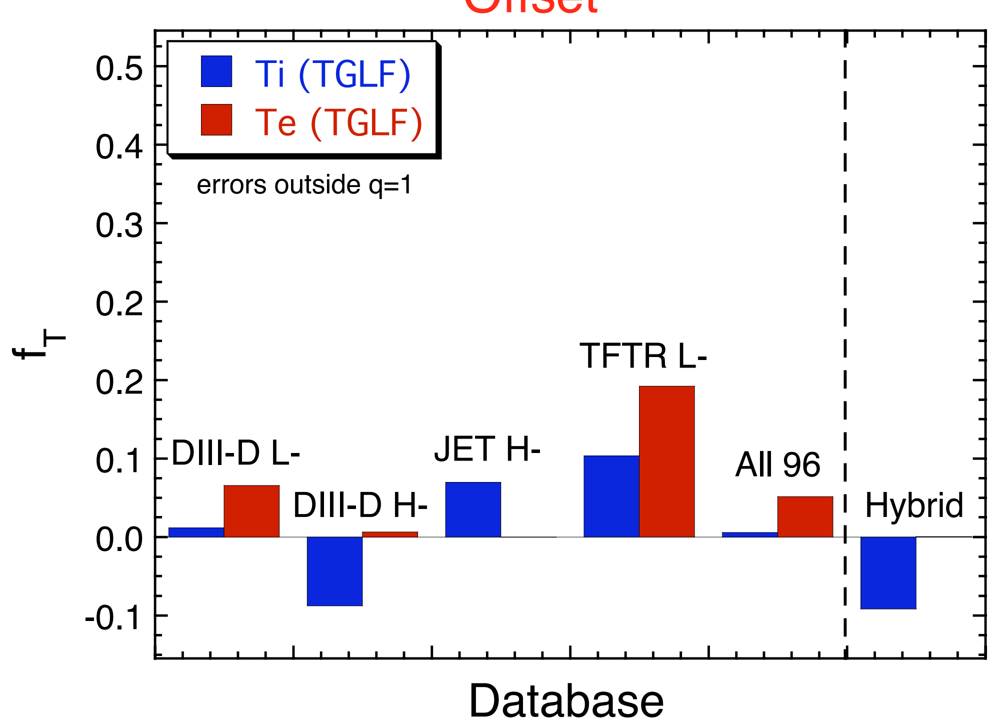
Local Errors Show TGLF Model Has Fairly Uniform Agreement Across DIII-D, JET, and TFTR Discharges

- **Avg RMS error for $[T_i, T_e]$ = [15%,16%]**
  - RMS errors in profiles computed outside q=1 to avoid influence by sawteeth
- **TGLF Avg RMS error for T_e smallest for H-modes, largest for DIII-D & TFTR L-modes**
- **TGLF has a small offset for DIII-D L- and H-modes and JET H-modes, but systematically overpredicts T_i,T_e for DIII-D and TFTR L-modes**

RMS error

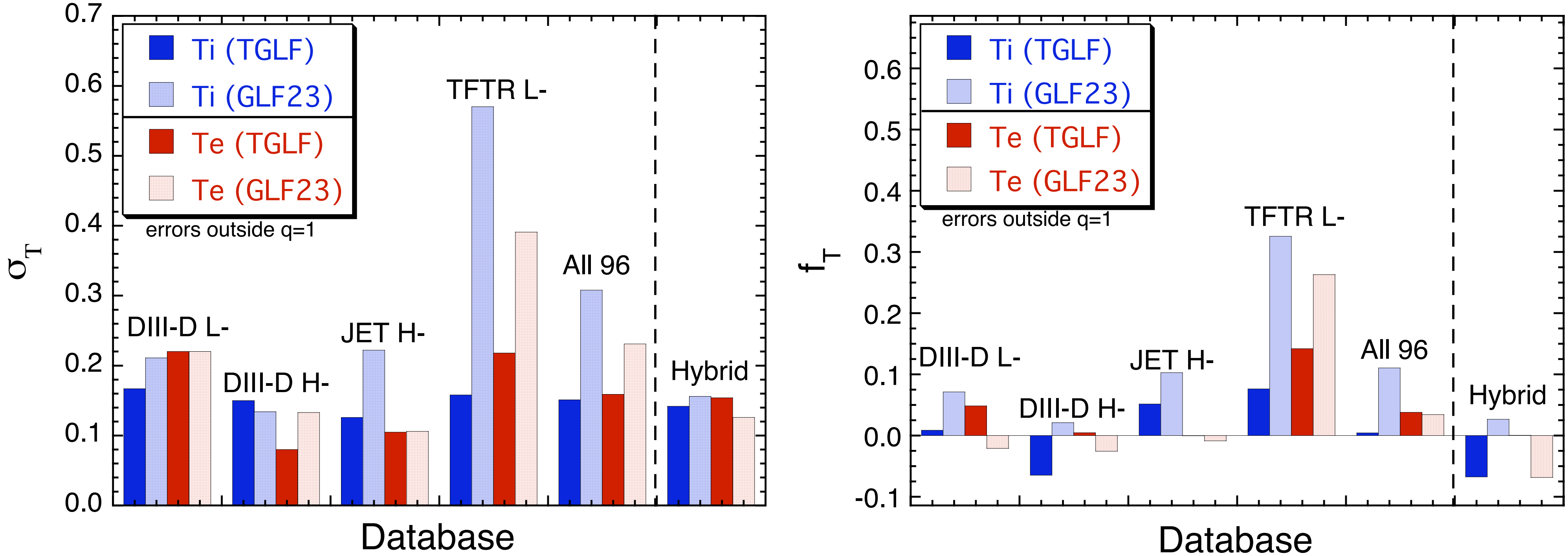


Offset



TGLF Model Has Lower Overall RMS Errors and Offsets in the Temperature Profiles Than the GLF23 Model

- **TGLF has avg RMS error for [T_i,T_e] of [15%,16%], GLF23 has [31%,23%]**
  - Comparable RMS errors for DIII-D L-, H-modes, and hybrids, but TGLF has noticably lower errors for JET and TFTR
- **TGLF has a smaller offsets JET and TFTR than GLF23**
- **TGLF has larger negative T_i offsets but smaller T_e offsets for DIII-D H-modes & hybrids**

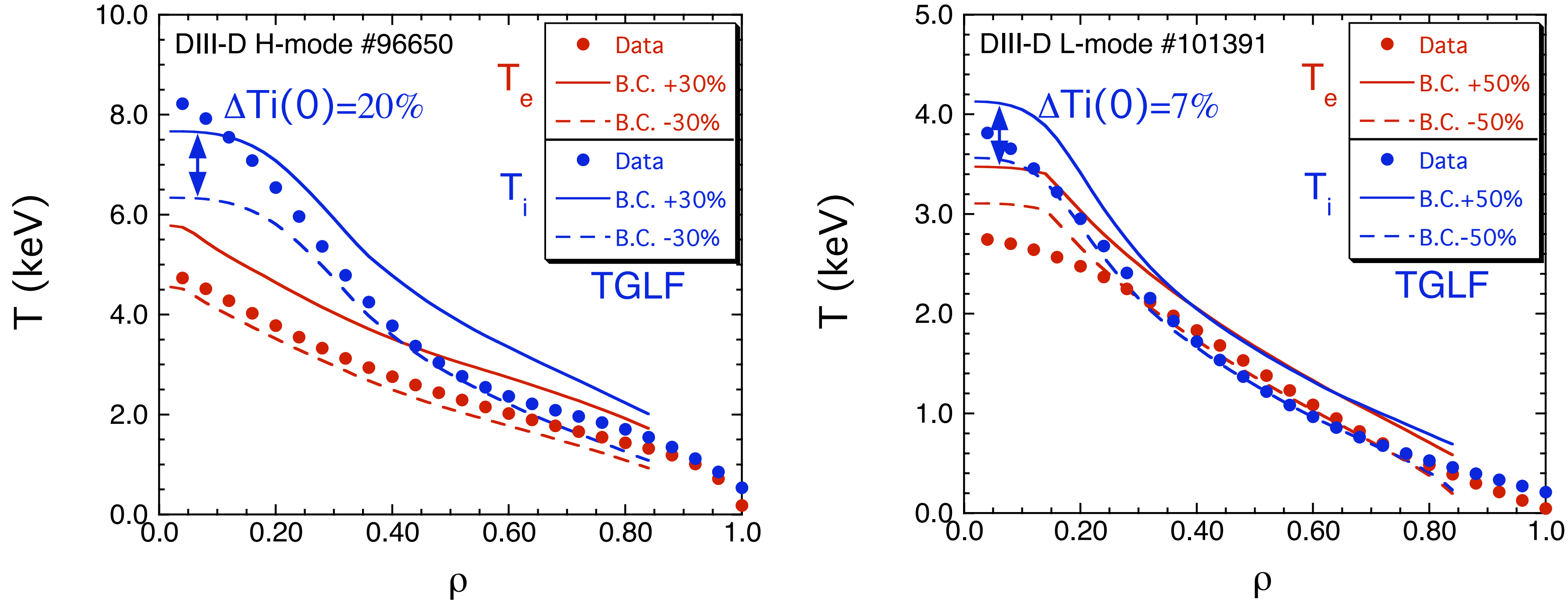


Sensitivity studies

Sensitivity to Boundary Conditions: TGLF Simulations Show L-mode Profiles Less Sensitive to Boundary Temperatures Than H-mode Profiles for DIII-D

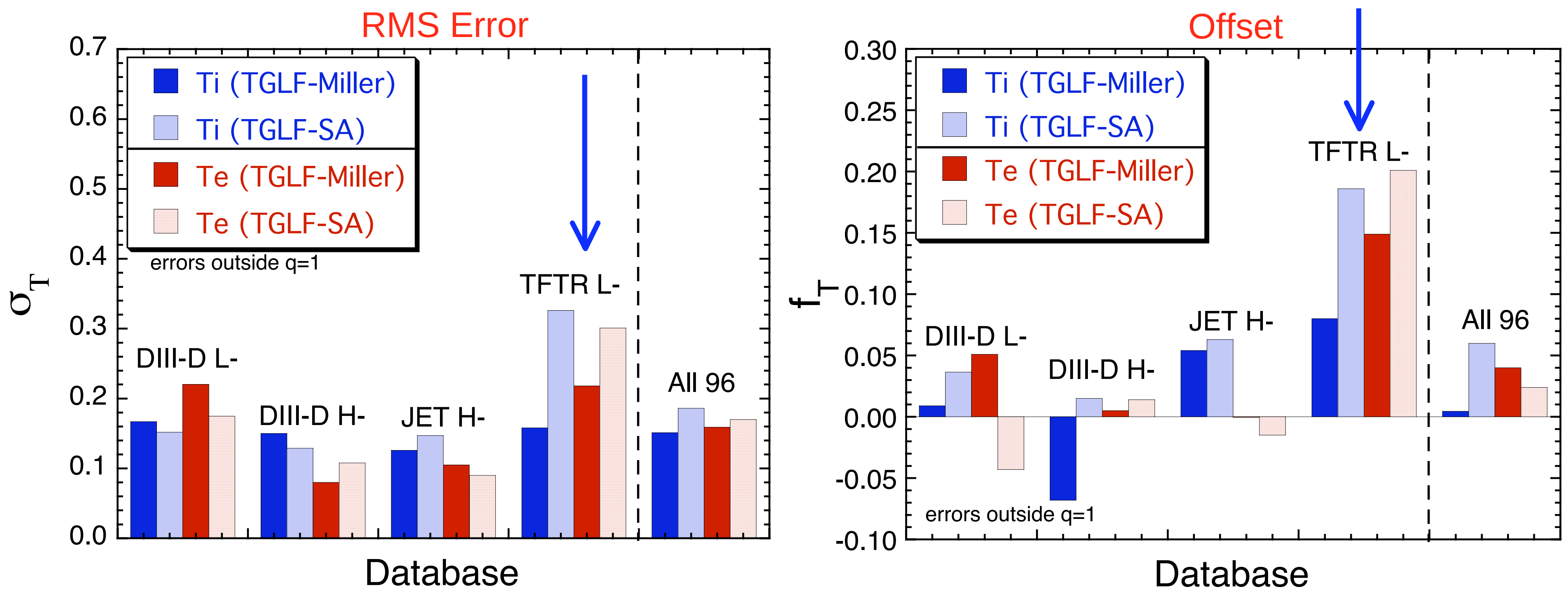
- **A measure of the sensitivity to the boundary temperature ("stiffness") is the ratio of the change in central temperature to the change in boundary temperature, $\Delta T_{io}/\Delta T_{BC}$**
- **The edge boundary temperatures were varied around the exp. values by +- 30% for a DIII-D H-mode and +-50% for a DIII-D L-mode**

H-mode: $\Delta T_{io}/\Delta T_{BC}$=0.20/0.30=0.67 L-mode: $\Delta T_{io}/\Delta T_{BC}$=0.07/0.50=0.14



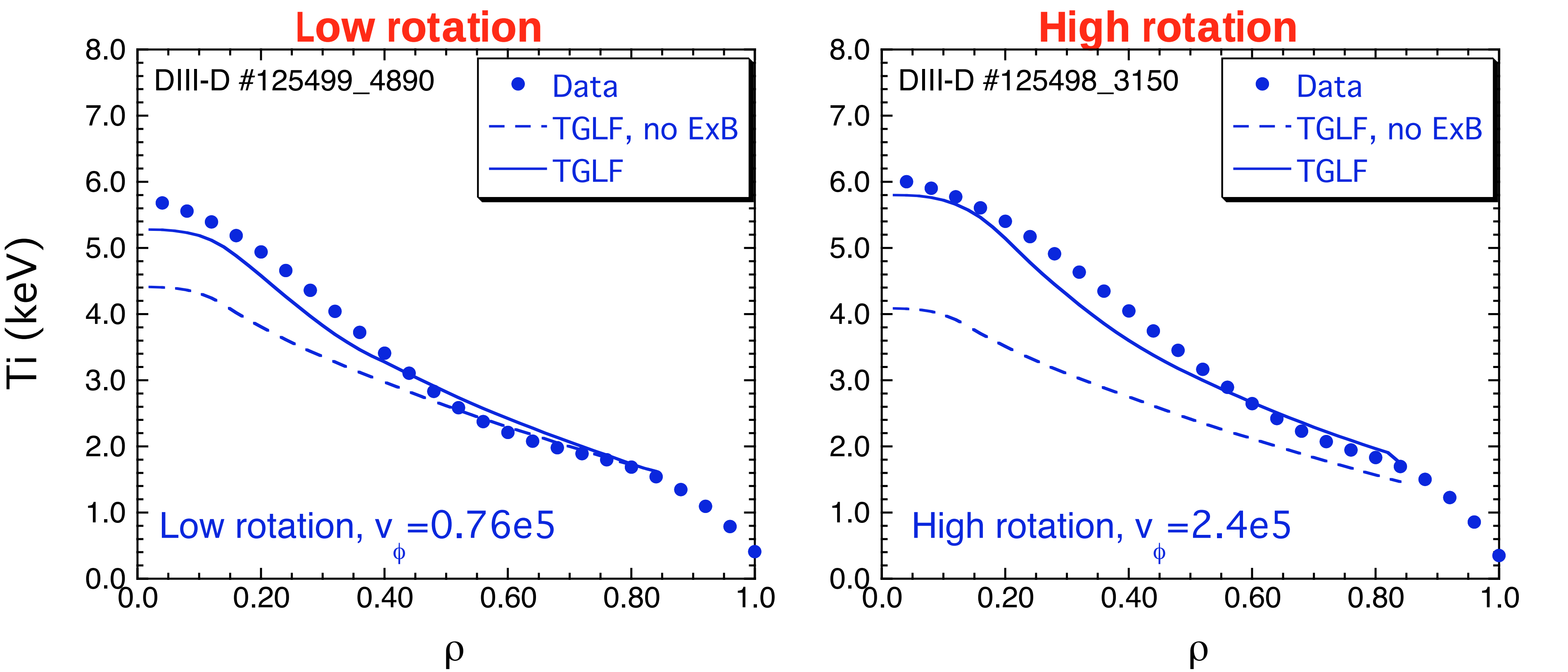
Sensitivity to Geometry: Miller Geometry Improves the Agreement of TGLF With Experimental Profiles

- **Miller geometry yields very little improvement for shaped tokamaks (DIII-D, JET) but yields surprisingly noticeable improvement for TFTR which is circular**
  - Finite aspect ratio in Miller geometry increases transport in TFTR compared to s-α but is compensated by elongation in shaped tokamaks (DIII-D, JET)



Sensitivity to ExB Shear: TGLF With ExB Shear Quench Rule Reproduces the Observed Change in Transport in a DIII-D Hybrid Rotation Scan

- Toroidal rotation varied by 3x, beam power changed to keep β fixed see Politzer UI1.00004
- TGLF shows ExB shear more important in high rotation case
- ExB shear has much less impact on T_e for hybrids because the electron transport is dominated by high-k modes



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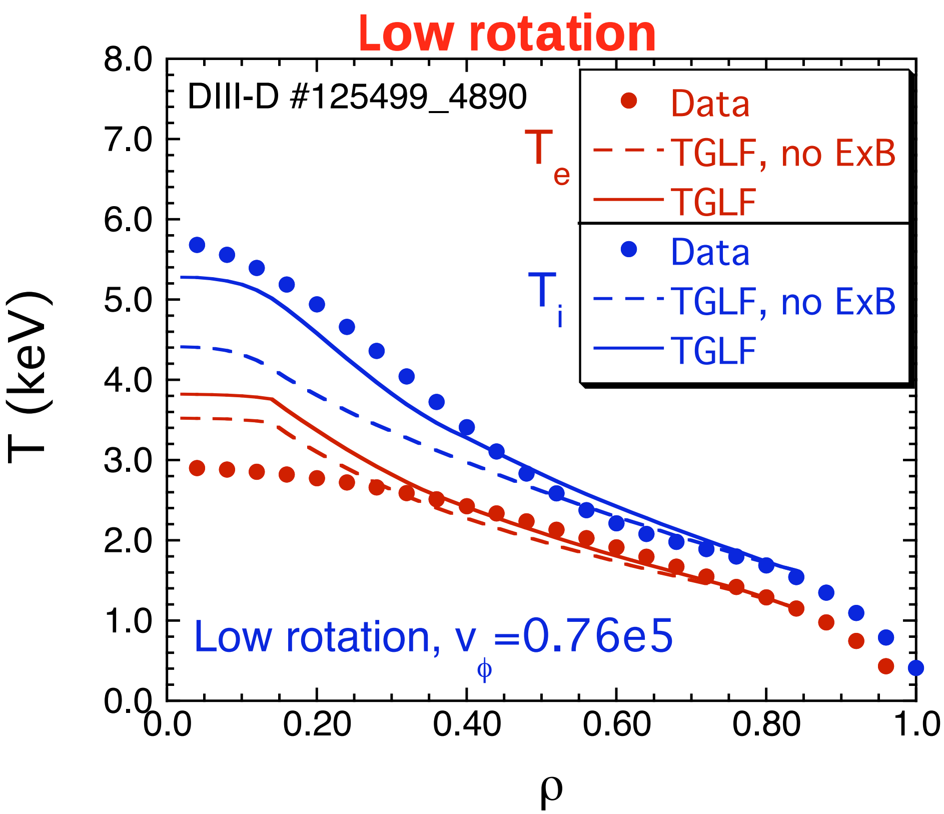
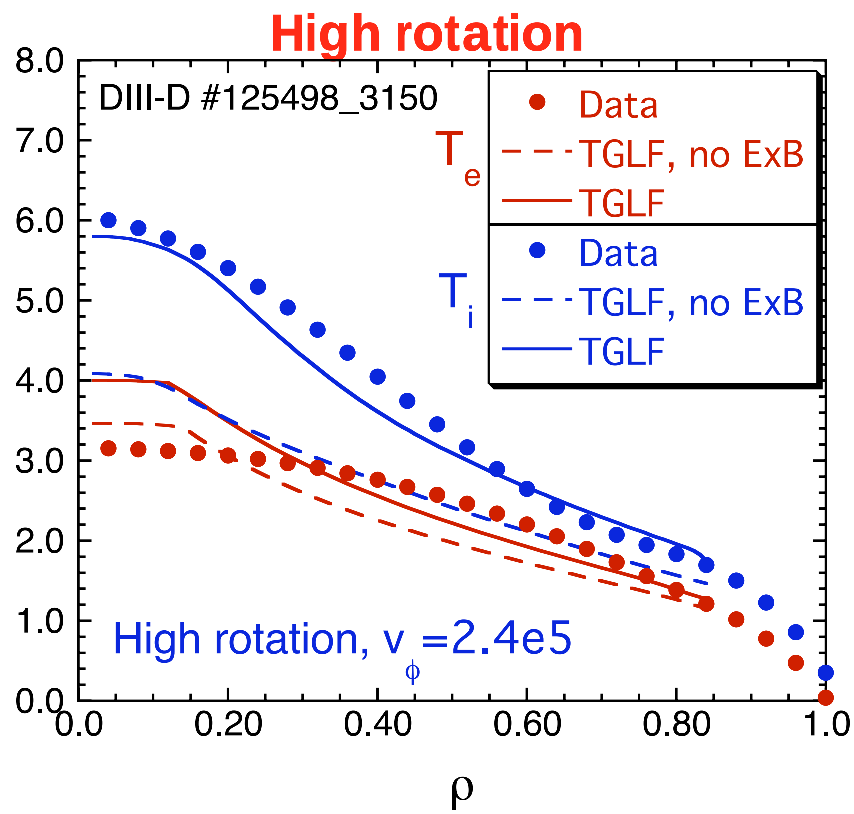
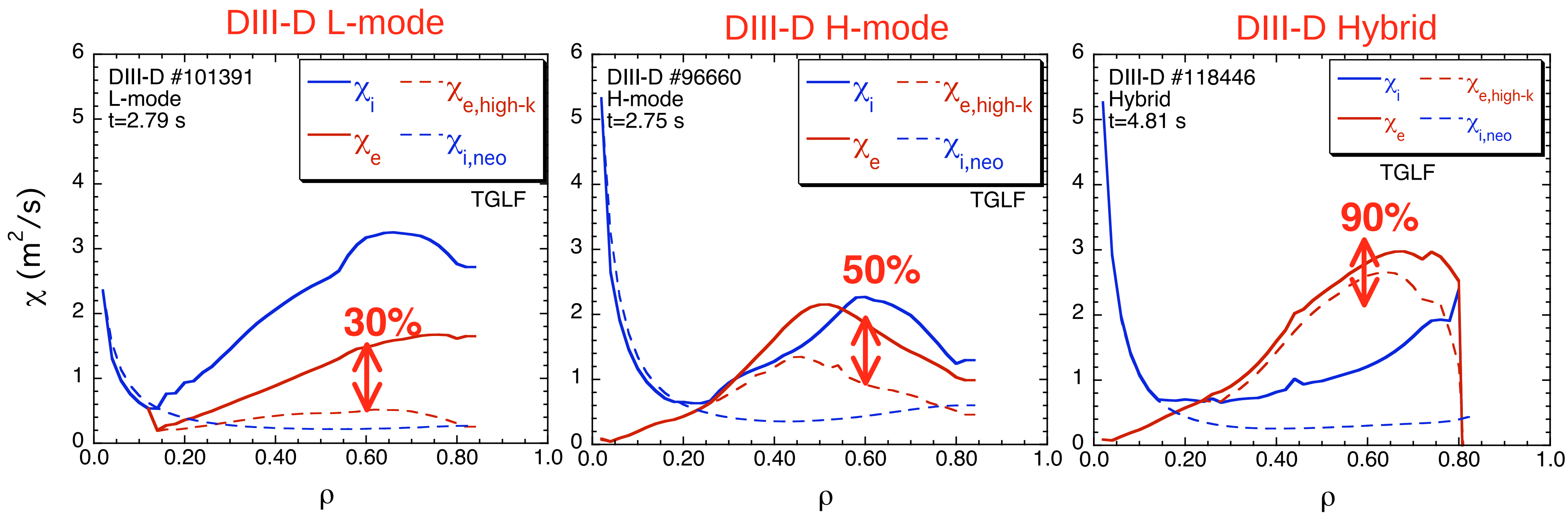




Sensitivity to High-k Modes: TGLF Predicts High-k Modes Can Dominate the Electron Transport in the Plasma Core

- **ETG coefficient in saturation rule determined by fitting GYRO simulation of GA STD case where $\chi_{e,high-k}$ / $\chi_{e,total}$ = 11% (k_y > 1, μ=30)**
- **TGLF has lower low-k contribution to χ_e than GLF23**
- **Suppression of ITG/TEM transport by ExB shear results in high values of $\chi_{e,high-k}$ / χ_e as χ_i approaches neoclassical**
  - Low q_{95} hybrids have largest $\chi_{e,high-k}$ / χ_e , L-modes have lowest $\chi_{e,high-k}$ / χ_e

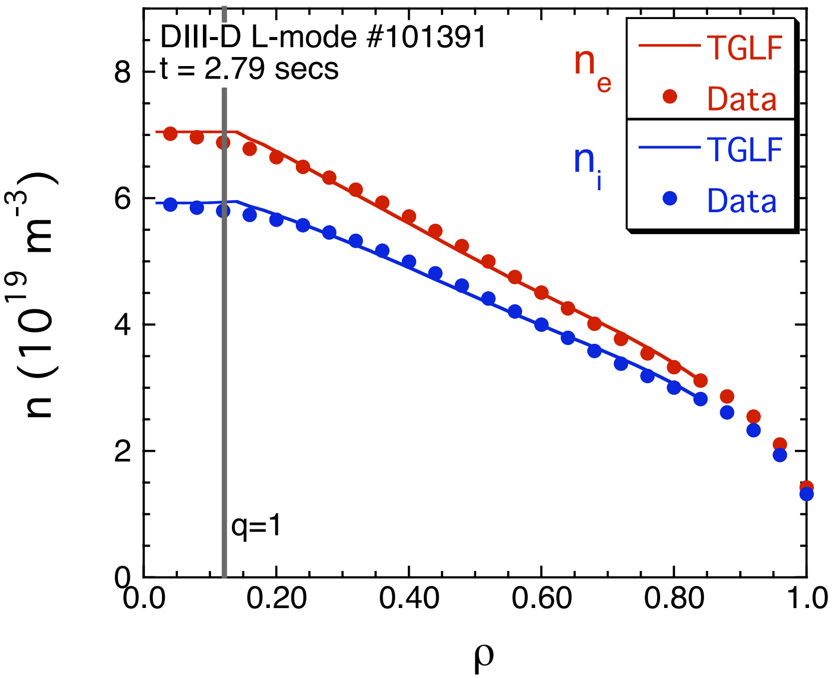


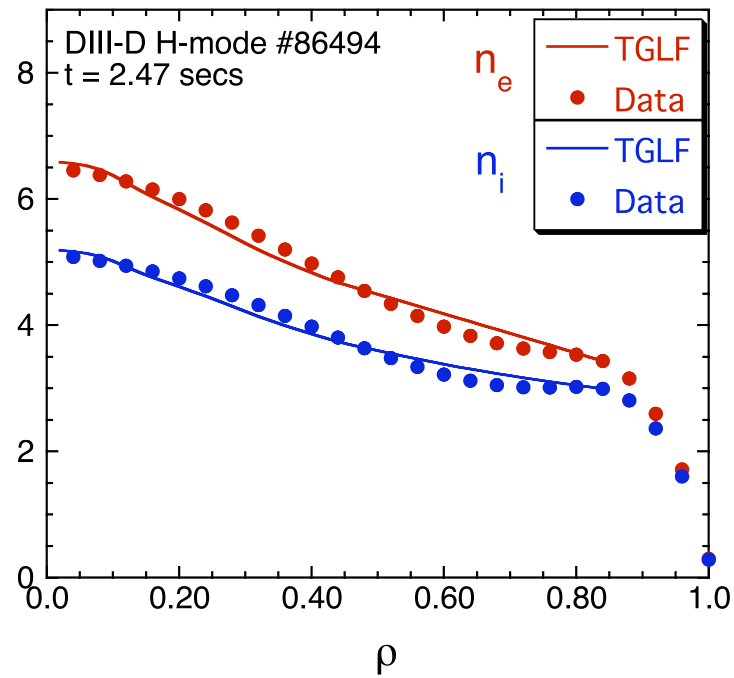
Sensitivity to Density Evolution: TGLF Reproduces Peaked Density Profiles and Has Low RMS Errors for Database

- **Density evolved along w/ Te, Ti with feedback on wall source to match line avg. density using the impurity, fast ion densities from exp. analyses**
  - Avg. σ_{ne} = 12% for 96 discharge database
- **RMS error in [Ti,Te] virtually unchanged from [15%,16%]**

Avg. σ_{ne}, f_{ne} for q>1

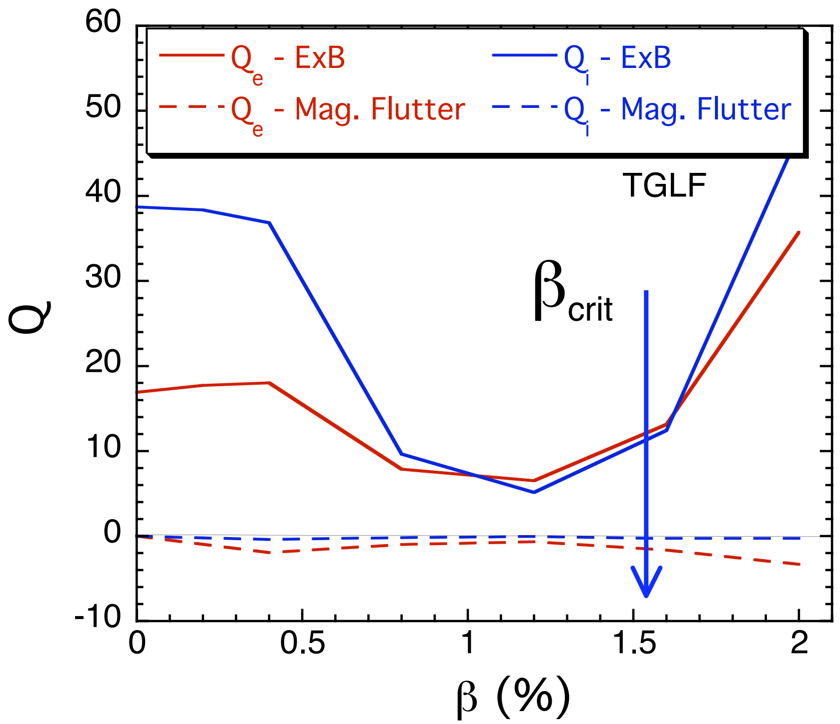
DIII-D L-	8 %, +1.2%
DIII-D H-	12 %, +8.0%
JET H-	16 %, +8.3%
TFTR L-	9 %, +3.4%

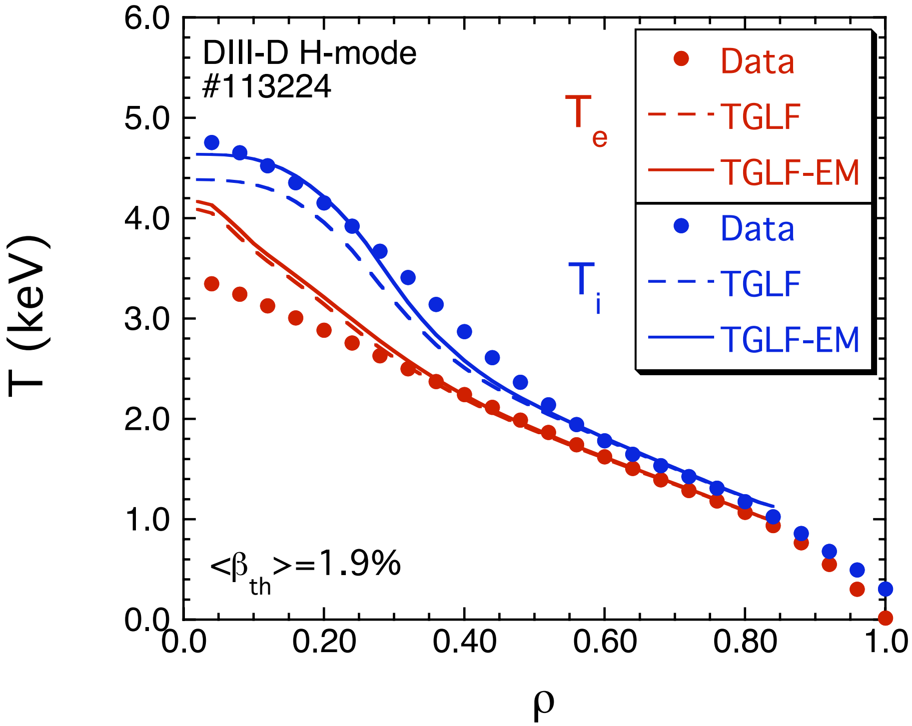




Sensitivity to Finite Beta: Finite β Found to Be Mildly Stabilizing in the Plasma Core of Discharges in Database

- **For STD case, energy fluxes decrease with β, then increase above ideal limit**
  - Magnetic flutter contribution not agreeing with GYRO, further work needed
- **RMS in T_i for hybrids decreases from 15% to 12% with finite β, smaller change in rms errors for DIII-D H-mode database**





Summary

- **Quasilinear saturation rule in TGLF shows remarkable agreement with large GYRO transport database of 82 simulations with Miller geometry !**
- **Comparison between the TGLF and GLF23 models for a database of 96 discharges from DIII-D, JET, and TFTR shows that TGLF exhibits 19% [2%] RMS [offset] error in Winc versus 36% [16%] for GLF23**
- **Average RMS errors in [T_i,T_e] are [15%,16%] for TGLF, [31%,23%] for GLF23**
- **TGLF predicts the high-k/ETG modes dominate the electron energy transport when the ion energy transport approaches neoclassical**
  - ETG dominant contributor to χ_e in DIII-D hybrid discharges especially for low q_{95} where low-k modes stabilized by ExB shear
  - High-k modes predicted to be important in the deep core of L- and H-modes
- **An ExB shear quench rule has been implemented in TGLF that fits GYRO nonlinear simulations at various elongations**
  - Quench rule well validated by rotation scans in DIII-D hybrid database, ExB shear more important in high rotation cases
- **TGLF accurately predicts density profile shapes with an average RMS error of 12% for 96 discharge database**

Future Work

- **Near term future work**
  - Include parallel velocity shear in TGLF equations, predict momentum transport including intrinsic rotation cases
  - Improve magnetic flutter transport fit to GYRO
  - Test model with high beta, low aspect ratio NSTX and MAST discharges
  - Test impurity dynamics
  - Include small effect of turbulent exchange
  - Examine possible data issues: MHD activity, time derivative terms, fast ion losses, beam deposition, dilution
  - Perform more GYRO ETG simulations for various conditions, compare to TGLF
  - Revisit ITER projections
- **Longer term future work**
  - Replace ExB shear rule with rotational ballooning mode net linear growth rate model; χ vs γ_E curve changes shape with aspect ratio
  - Study near edge turbulence, revise profile database with more accurate EFITs, and extend modeling toward edge
  - Add nonlocal transport effects, broken gyro-Bohm scaling